

## **Leukaemia and low dose radiation:- Is there an association between leukaemia and cumulative external dose amongst the British Nuclear Fuel plc. (BNFL) workers?**

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### **Abstract.**

A detailed examination of the BNFL leukaemia data is presented, for the period 1946-1995, using the recently assembled company wide BNFL epidemiological database and the BNFL leukaemia case-control data set. The association of this occupationally exposed cohort is examined with respect to both leukaemia mortality and leukaemia morbidity. The excess relative risk for total leukaemia excluding chronic lymphatic leukaemia amongst the BNFL radiation workers was found to be  $3.64 \text{ Sv}^{-1}$  (90% CI  $-0.13-11.22$ ); for Sellafield and Springfields this figure was  $7.99 \text{ Sv}^{-1}$  (90% CI  $1.50-29.5$ ) and  $-1.97 \text{ Sv}^{-1}$  (90% CI  $<-2.23-6.11$ ) respectively. A 14-20% increase in risk is noted when dosimetry adjusted for measurement error, is used to determine the excess relative risk. The association between leukaemia and cumulative external radiation is found to be particularly associated with the Sellafield plant; the Springfields plant gave consistently negative risk estimates.

### **1. Introduction.**

Despite the fact that detrimental health effects of radiation were reported within months of Roentgen's discovery of radiation<sup>1</sup>, it was not until 1944, nearly 50 years later, that March published results<sup>2</sup> showing the radiologists in the USA had a much higher mortality due to leukaemia than did other physicians. One of the earliest findings of the atomic bomb survivors studies<sup>3</sup> was the elevated risk of leukaemia, particularly amongst the young. Other populations<sup>4</sup> exposed to high dose and high dose-rate radiation have also shown elevated risk of leukaemia. Radiological protection standards are based on these studies using models which extrapolate these acute exposures to low dose, low dose-rate exposed populations. Studies of occupationally exposed workers permit a direct assessment of the validity of these extrapolations. In the largest of these studies published to date, the International Agency for Research on Cancer's (IARC) combined analysis<sup>5</sup> of cancer mortality amongst the nuclear industry workers of three nations, a statistically significant association, at the 5% level, between external radiation and leukaemia was reported ( $p=0.046$ ). Sellafield's contribution to the statistical information was almost 35%. We present here the preliminary results of the BNFL leukaemia study.

At the end of 1995, BNFL had 4 operational plants, namely Springfields, Sellafield, Capenhurst and Chapelcross. Responsibility for these plants had been transferred from the Ministry of Supply to the United Kingdom Atomic Energy Authority in 1954 and subsequently to BNFL in 1971. Since 1995, BNFL has acquired further Magnox power stations, namely Bradwell in Essex, Dungeness A in Kent, Hinkley Point A in Somerset, Oldbury in Avon, Sizewell A in Suffolk and Wylfa in Anglesey. Together they represent the various parts of the nuclear industry.

During the Second World War the Springfields site, near Preston, Lancashire, was developed as a poison gas factory by the Ministry of Supply. On March 28<sup>th</sup> 1946, Clement Attlee's government named Springfields as the site at which uranium metal would be produced in the United Kingdom. In 1948 the first two uranium billets were cast and in 1952 the first cylinders of uranium hexafluoride were produced. In 1954 the newly formed United Kingdom Atomic Energy Authority took over the responsibility for the site from the Ministry of Supply. By 1963 it was producing 200,000 fuel elements per year, and by the end of the 1980s Springfields was supplying fuel to all 18 commercial reactors in the UK, with products also being exported.

Uranium ore concentrates from around the world are received at Springfields. The ore, usually extracted from open-cast mines, contains on average 0.15% uranium. The ore is ground and treated and the solid uranium concentrate, known as yellowcake, is formed. The yellowcake contains around 75% uranium. When the yellowcake is received at Springfields it is first dissolved in nitric acid to produce uranyl nitrate. This is then purified and concentrated before it is converted to uranium tetrafluoride, by a chemical process which includes reaction at high temperature with air, then hydrogen, then hydrogen fluoride. At this point the production process branches. Some uranium tetrafluoride is converted to uranium metal for magnox reactors and some is reacted with flourine to produce uranium hexafluoride, which is sent for enrichment prior to conversion into uranium oxide fuel.

The Sellafield plant is situated on the Cumbrian coast of northwest England, 15 Km south of the Westlakes Research Institute. The two Windscale Piles were uranium metal, graphite moderated, air-cooled, open-circuit nuclear reactors designed to produce plutonium for the UK atomic weapons programme. Construction work on the Windscale Piles began in September 1947 and by the early summer of 1950, Pile Number 1 was complete and the fuel elements were loaded. Pile number 1 achieved criticality in October 1950, and Pile number 2 in June 1951. By 1952 the spent fuel reprocessing plant was in operation. The reactors were subsequently closed and the reprocessing plant replaced. The Sellafield plant reprocesses and stores spent nuclear fuel for both domestic and international customers.

When the Atomic Energy production division of the Ministry of Supply was set up in 1946, a plant was needed to produce highly enriched uranium for defence purposes. Construction work began at Capenhurst in Cheshire in 1950 and the gaseous diffusion plant started operating in 1953.

The high enrichment section of the plant was closed in 1962, but the remainder continued to operate to produce material to fuel the second generation of nuclear power stations, which were then being designed. However, by 1969 it had become clear that the gas centrifuge process was a more attractive alternative to gaseous diffusion as an enrichment technology and thus should eventually take over. The diffusion plant continued to operate satisfactorily until 1982.

Development work on the gas centrifuge process began at Capenhurst in the late 1960s, with a pilot centrifuge plant starting operation in 1973. An industrial scale plant, which has now been shut down, was brought on stream in 1977 and a second plant started operation in 1983. A third centrifuge plant was completed in 1989 with the centrifuges being installed as required. Between 1965 and 1987, a small plant operated at Capenhurst, processing tritium for defence purposes<sup>6</sup>.

The Chapelcross plant is located some 3Km north east of Annan, in Dumfriesshire, Scotland. The main activity of the plant is the operation of the four 50MW Magnox gas cooled reactors. Magnox reactors are graphite moderated and carbon dioxide cooled. The natural uranium metal fuel elements are contained in magnesium alloy cans. Construction of the plant began in 1955 and the first reactor began operating in February 1959, with the other three all operational by the 2<sup>nd</sup> May 1959, the official opening day. In 1976, BNFL was awarded a contract by the Ministry of Defence to supply tritium. Tritium is a radioactive isotope of hydrogen, with a half-life of about 12.5 years and is 'commercially' produced by irradiating <sup>6</sup>Li in a nuclear reactor. By 1980, tritium was being produced at Chapelcross.

In 1996, the Nuclear Installations Inspectorate allowed the Chapelcross plant to operate for a further 10 years, conditional on satisfactory results from ongoing inspection and monitoring, giving the reactors a potential operating life of 50 years.

## 2. Study population.

The study population consisted of the 61,470 employees of BNFL and the United Kingdom Atomic Energy Authority who were ever employed at the Springfields, Sellafield, Capenhurst or Chapelcross plants of BNFL before 1<sup>st</sup> January 1996. The study contains 1,431,207 person-years of follow-up, with a mean follow-up period of 23.3 years.

Tracing data and cancer registration data were obtained from the Office for National Statistics (ONS), at Southport and the General Register Office in Edinburgh. Vital status is determined from the tracing returns, though sometimes other data are used if there are inconsistencies found in the data. The vital status at 31<sup>st</sup> December 1995 is given in table 1 below.

|                     | Radiation workers |        | Non-radiation workers |         | Total            |
|---------------------|-------------------|--------|-----------------------|---------|------------------|
|                     | Male              | Female | Male                  | Female  |                  |
| Alive               | 28,750            | 2909   | 10090                 | 6223    | <b>47,972</b>    |
| Deaths: all causes  | 7383              | 137    | 4890                  | 1088    | <b>13,498</b>    |
| Deaths: all cancers | 2074              | 37     | 1318                  | 344     | <b>3,773</b>     |
| Deaths: leukaemias  | 58                | 0      | 26                    | 6       | <b>90</b>        |
| <b>Total</b>        | 36,133            | 3,046  | 14,980                | 1,432   | <b>61,470</b>    |
| <b>Person-years</b> | 798,638           | 51,287 | 403,548               | 177,734 | <b>1,431,207</b> |

**Table 1: Vital status on 31/12/95.**

For the cohort study, cases are defined as those individuals who have leukaemia as the underlying cause of death on their death certificates. For the case-control study, the definition of cases is extended to include those individuals who have a leukaemia as either the underlying or a contributory cause of death, or have been registered for leukaemia.

## 3. Dosimetry.

Dosimetry data were collected to demonstrate compliance with radiation protection regulations, not for the purpose of epidemiological research. The accuracy and precision of the individual external dose readings is dependent on when the film badge was issued, the technology in use at the time, the exposure regime at the time

and the protocol adopted at the time for processing and recording the film badge data. In this analysis annual summaries of the workers external whole body radiation dose data, lagged by 2 years, are used. Adjusted dose estimates were also calculated for the cohort, in the spirit of that described by Pierce<sup>7,8</sup> et al. The distribution of true doses was assumed to be Weibull, and the dosimetry error distribution was assumed to be log-normal with 30% error. In the case-control study, doses for the controls were truncated and pro-rated, at the time of the case and then lagged two years. Future work will use the individual film badge doses for the cases and controls. Some Sellafield workers are also exposed to plutonium. Special assessment of plutonium doses have been made, though in this report, the analysis will be restricted to the use of the flagged plutonium data. The total dose received by the BNFL radiation workers up to 31/12/95 was 2210 person-Sieverts; the Springfield radiation workers have received 332 person-Sieverts, the Sellafield radiation workers 1675 person-Sieverts, the Capenhurst radiation workers 22 person-Sieverts and the Chapelcross radiation workers 181 person-Sieverts. Figure 1 shows how the distribution of annual doses has decreased with time at BNFL and its component sites. The mean annual dose for the radiation workers at BNFL over the study period was 5.60 mSv. The mean annual dose at Springfields, Sellafield, Capenhurst and Chapelcross was 2.49, 7.65, 1.23 and 7.39 mSv respectively. For comparison, the mean dose received by the UK population from all natural sources is estimated<sup>9</sup> to be about 2.2mSv.

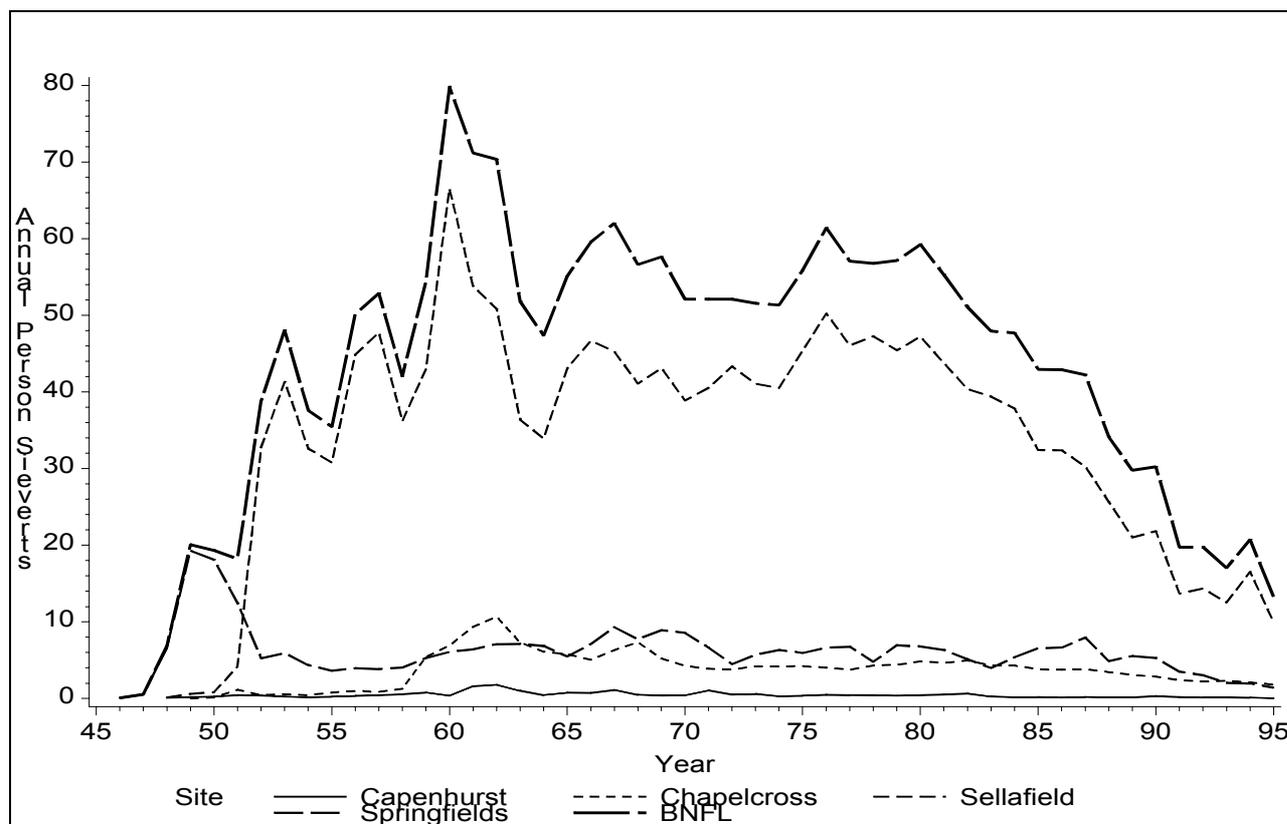


Figure 1. Distribution of annual dose amongst the BNFL radiation workers; by site.

#### 4. Analysis.

The preliminary analysis sought to find potential confounders<sup>10,11</sup> that should, in addition to age, sex and calendar year, be adjusted for in the main analysis. These potential confounders included site of employment, industrial status (industrial or non-industrial), which is regarded as a measure of socio-economic status, worker status (serving staff, retired staff, as well as transferrals and other staff), first year of joining, length of exposure, length of service and length of follow-up. These covariates were examined in the cohort for radiation workers for all causes, all cancers and leukaemias. The magnitude of the potential confounders was examined by noting the difference in the rate ratios (RRs) after stratifying by the confounder. Adjustment for confounders was then made by stratification in the cohort study. In the case-control study, the confounders were dealt with by matching, with due consideration being given to whether the confounder is on the causal path.

SMRs were used to compare the mortality experience of the cohort with the leukaemia mortality rates for the populations of England and Wales. To reduce some of the biases resulting from comparison with the national population rates and other factors such as differential selection resulting from geographical and socio-economic considerations, the mortality rates of the radiation workers were compared with those of non-radiation

workers and rate ratios were determined. The relationship between mortality due to leukaemia and cumulative external radiation exposure was examined using a trend test<sup>12,13</sup> to assess the statistical significance of any association. The excess relative risk model<sup>14</sup>, assuming the excess relative risk (ERR) is time invariant, was fitted for total leukaemias and total leukaemias excluding chronic lymphatic leukaemia (CLL), to determine the change in cancer risk per unit of cumulative external radiation dose. Evidence<sup>15</sup> from the atomic bomb survivors shows that this assumption of time invariance is not valid in high dose studies, with the ERR for leukaemia reducing with time after exposure. However, in a recent report<sup>16</sup> on nuclear workers, there was insufficient power to detect any variation in the leukaemia ERR with time from exposure. This assumption will be examined in more detail in a future report. The cumulative external dose was lagged by 2 years for comparability with other studies that also assume a 2 year latency period for leukaemias. The ERRs were determined using Epicure's (version 2.10)<sup>17</sup> Amfit and Pecan modules; for the cohort study, Amfit was used to determine the ERR on the grouped data; Pecan was used to determine the ERR on the individual data for the case-control study. TAB4 (version 4, release 1)<sup>18</sup> and SAS (version 6.12, TS level 0060)<sup>19</sup> were also used to perform the analyses.

For SMRs and RRs, the p-values quoted are for two-sided hypothesis tests. For the trend analysis, the p-values quoted are for a one-sided test, since our prior hypothesis is that workers who have been occupationally exposed to external radiation would be expected to show increased cancer mortality and registration rates.

## 5. Results.

### 5.1 Potential confounders.

Significant differences in RRs between non-industrial and industrial workers were noted for all causes mortality (RR=0.76, 95% CI=0.71-0.80), and all cancer mortality (0.72 95% CI=0.65-0.91). Due to the small number of leukaemias, there was insufficient power to detect a difference in rates. Similarly, differences were noted in the rates for worker status groups as well as amongst the site of employment. This difference reflects the North-South gradient of mortality in the UK<sup>20</sup>. No significant differences were found for length of service, length of exposure or year of joining. There was a slight increase in mortality noted with increasing length of follow-up. The cohort analysis thus proceeded with stratification by age group, (5-year groups, 15-19, 20-24, ..., 80-84 and 85+), sex, individual calendar year, employment site as well as by industrial status and worker status. For the trend analysis and excess relative risk calculations 10 dose groups were used, 0-4, 5-9, 10-19, 20-49, 50-99, 100-149, 150-199, 200-299, 300-399 and 400+ mSv.

For the case-control study the controls were randomly selected from the relevant risk sets after matching on sex, site, industrial status (industrial and non-industrial workers) and date of birth. Controls also had to be alive at the time of the event i.e. either death or registration. Where possible, dates of birth were matched within plus or minus one year. When it was not possible to identify sufficient controls, the date of birth criterion was relaxed by one-year increments until sufficient controls were selected. There were 7 cases that were employed at two different sites. These individuals were assigned to their last site of employment.

### 5.2 Cohort results.

The SMR and RR results for BNFL are shown in table 2, by leukaemia sub-type. Table 2a covers the period up to 1968, and table 2b covers the period from 1968 when the more detailed International Classification of Diseases revisions 8 and 9 were used to code the deaths. None of the rate ratios were significantly different from unity. Table 3 shows how total leukaemia and total leukaemia excluding CLL varies across the sites. Again, none of the rate ratios were significantly different from unity. Table 4 shows the results for the trend analysis and excess risk estimates for BNFL and for Sellafield and Springfields for total leukaemia and total leukaemia excluding CLL. (There were insufficient numbers of cases at Chapelcross and insufficient number of cases amongst the radiation workers at Capenhurst to obtain informative results for these sites.) The results are presented for radiation workers as well as all workers. For comparison, results are also presented using the adjusted dosimetry results. For Sellafield the results are also presented for the radiation workers who were also monitored for plutonium exposure as well as for the radiation workers not monitored for plutonium.

### 5.3 Case-Control results: mortality.

Between 1946 and 1995, there were 111 deaths identified that had leukaemia as either an underlying or contributory cause of death amongst the BNFL workforce. Between 1971-1995 there were 67 leukaemia cancer registrations at BNFL. Table 5 shows the distribution by sub-type and table 6 shows how they were distributed by sex and industrial status amongst the sites. Table 7 shows characteristics of the cases with respect to year of employment, age at year of event and mean cumulative external dose. The distribution of mean doses of the mortality and registration cases are shown in Table 8. Table 9 shows the mean doses for the cases and controls, for both mortality and registrations, at the different sites. Tables 10 and 11 present the ERR results for mortality and morbidity respectively for radiation workers and all workers at BNFL and Springfields and Sellafield.

## 6. Discussion.

The results from the cohort study show that there is no statistically significant excess of leukaemias at BNFL or the individual sites when compared with the population of England and Wales. When the radiation workers were compared with the non-radiation workers, no statistically significant difference was found in the mortality rates due to leukaemia. However, when the trend statistics are examined there is a significant statistical association noted between cumulative whole body external radiation and leukaemia. There is evidence<sup>4</sup> that CLL is known not to be induced by radiation and when CLL is excluded this association is strengthened. For radiation workers the z-statistic, for trend, increases from 2.02 to 2.15. There are essentially two major contributors to the BNFL association, Springfields and Sellafield. The other two sites have either insufficient numbers (Chapelcross) or insufficient radiation workers (Capenhurst) to make any meaningful contribution. At Springfields the association is consistently negative, whereas at Sellafield the association is consistently positive.

The excess relative risk for the BNFL radiation workers to mortality due to leukaemia excluding CLL is found to be  $3.64 \text{ Sv}^{-1}$  (90% CI  $-0.13-11.22$ ), which is consistent, though a little higher, than that reported in the second analysis<sup>16</sup> of the National Registry for Radiation Workers ( $2.55 \text{ Sv}^{-1}$  (90% CI  $0.03-7.16$ )) or IARC's analysis of the nuclear workers in three nations<sup>5</sup> ( $2.18 \text{ Sv}^{-1}$  (90% CI  $0.13-5.7$ )), both of which contain, and whose results are largely dependent on, a sub-cohort of the Sellafield workers. For morbidity due to leukaemia excluding CLL it is found to be similar at  $3.33 \text{ Sv}^{-1}$  (90% CI  $<-2.81-13.25$ ). For the Sellafield radiation workers the excess relative risk for total leukaemia excluding CLL was found to be  $7.99$  (90% CI  $1.50-29.5$ ). This is lower than that reported by Douglas<sup>21</sup> et al. and is a consequence of the longer period of follow-up<sup>22</sup>.

Plutonium is an alpha emitter that is deposited on the bone and may therefore be expected to be leukaemogenic by having an effect on the marrow. Whilst this study has little power to detect a difference between plutonium radiation workers and non-plutonium radiation workers, the ERR for the latter is higher than that of the former. An opposite result may well be expected, particularly as the plutonium radiation workers contain some of the more heavily exposed cases in the cohort. This evidence suggests that if there is a significant leukaemogenic exposure at Sellafield, other than external radiation, then it does not appear to be plutonium.

Random errors in dosimetry measurements are known to cause systematic biases in the risk estimates obtained using the linear dose response model. When the adjusted dosimetry estimates are used, the ERR estimates are increased between 14-20%. When this methodology was applied to the atomic bomb survivors, Pierce<sup>6</sup> et al found that their adjusted estimates were increased by 6-17%. The assumptions made in the application of this methodology may not be valid when applied to the nuclear workers, who receive much smaller fractionated doses where the errors associated with smaller doses are large. Gilbert et al<sup>23</sup> have recently made an assessment at the Hanford plant, USA, and identified several sources of uncertainty and biases. When she<sup>24</sup> applied the calendar – year specific factors, determined from the assessment, for converting recorded dose to estimates of dose to the bone marrow, she found that the ERR for leukaemia excluding CLL using the adjusted dosimetry, increased the estimate by 40%.

## 7. Conclusion.

Is there an association between leukaemia and cumulative external dose amongst the British Nuclear Fuel plc. workers? The answer is in the affirmative. There is an association between leukaemia mortality and leukaemia morbidity and cumulative external dose. This association is found at the Sellafield plant, as expected, but not at the Springfields plant. The point estimate for the ERR found at the Sellafield plant is higher than that derived from the atomic bomb survivors or any of the other exposed cohorts. This may just be a reflection of the large confidence interval of the estimate or may be due to other unidentified factors. Whilst internal exposure to plutonium is expected to be one of these other risk factors, the evidence here may suggest that this is not the case. Springfields, which has potential for internal exposure to uranium, shows a consistently negative association with radiation. Future work will focus on the question of adjusted dosimetry and also on ways of combining the information derived from cancer mortality and cancer registration data. The case-control data set will be used to explore further putative associations.

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## 9. References.

1. Doll R, Hazards of ionizing radiation: 100 years of observation on man. *Br. J. Cancer*, **72**, 1339-1349, 1995.
2. March H C, Leukaemia in radiologists. *Radiology*, **43**, 275-278, 1944.
3. Valentine W N, Present status of the study of the incidence of leukaemia among individuals surviving exposure to the atomic bomb in Hiroshima and Nagasaki. *ABCC Report*, 1951.
4. United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR 1994). Sources and effects of ionizing radiation, 1994 report to the General Assembly with scientific annexes, New York, United Nations.
5. Cardis E, Gilbert E S, Carpenter L, Howe G, Kato I, Fix J, Salmon L, Cowper G, Armstrong B K, Beral V, Douglas A, Fry S A, Kaldor J, Lavé C, Smith P G, Voelz G and Wiggs L, Combined analysis of cancer mortality among nuclear industry workers in Canada, the United Kingdom and the United States of America. *IARC Technical Report No. 25*, Lyon, 1995.
6. Jackson D, Gray J, Powell F and Roscoe P A, Reconstruction of discharges and environmental doses from a former tritium facility at BNFL Capenhurst. *J. Radiol. Prot.* **17**, 239-252, 1997.
7. Pierce D A, Stram D O and Vaeth M, Allowing for random errors in radiation exposure estimates for the atomic bomb survivor data. *Radiat. Res.* **123**, 275-284, 1990.
8. Pierce D A, Stram D O, Vaeth M and Schafer D W, The errors-in-variables problem: Considerations provided by radiation dose response analyses of the A-bomb survivor data. *J. Am. Stat. Asc.* **87**, 351-359, 1992.
9. Hughes J S and O'Riordan M C, Radiation exposure of the UK population: 1993 review. Chilton, NRPB Report R263, London, HMSO, 1993.
10. Gilbert E S, Some confounding factors in the study of mortality and occupational exposures. *Am. J. Epid.* **116**, 177-188, 1982.
11. Pearce N, Methodological problems of time related variables in occupational cohort studies. *Rev. Epidém. et Santé Publ.* **40**, s43-s54, 1992.
12. Mantel N, Chi-Square tests with one degree of freedom. Extensions of the Mantel-Haenszel procedure. *J. Am. Stat. Asc.* **58**, 690-700, 1963.
13. Hakulinen T, A Mantel-Haenszel statistic for testing the association between a polychotomous exposure and a rare outcome. *Am. J. Epid.* **113**, 192-197, 1981.
14. Prentice R L and Mason M W, On the application of the linear relative risk regression models. *Biometrics*, **42**, 109-120, 1986.
15. Pierce D A, Shimizu Y, Preston D L, Vaeth M and Mabuchi K, Studies of the mortality of A-bomb survivors. Report 12, part 1. Cancer: 1950-1990. *Radiat. Res.* **146**, 1-27, 1996.
16. Muirhead C R, Goodill A A, Haylock R G E, Vokes J, Little M P, Jackson D A, O'Hagan J A, Thomas J M, Kendall G M, Silk T J, Bingham D and Berridge G L C, Second Analysis of the National Registry for Radiation Workers: Occupational Exposure to Ionizing Radiation and Mortality. Chilton, *NRPB report R307*, London, HMSO, 1999.
17. Epicure, Hirosoft International Corporation, Seattle, WA, June 1998.
18. TAB4, Westlakes Scientific Consulting, 1998.
19. SAS, SAS Institute. Inc, Cary, NC, USA, 1996.
20. Law M R and Morris J K, Why is the mortality higher in the poorer areas and in more northern areas of England and Wales? *J. Epid. Comm. Health*, **52**, 344-52, 1988.
21. Douglas A J, Omar R Z and Smith P G, Cancer mortality and morbidity among workers at the Sellafield plant of British Nuclear Fuels. *Br. J. Cancer* **70**, 1232-1243, 1994.
22. Preston D, Issues in the estimation of leukaemia risks from atomic bomb survivor studies. Report 22, 7-10, British Institute of Radiology, The future of human radiation research, 1991.
23. Gilbert E S, Fix J J and Baumgartner W V, An assessment of bias and uncertainty in recorded dose from external sources of radiation workers at the Hanford site. *Health Phys.* **70**, 336-345, 1996.
24. Gilbert E S, Accounting for errors in dose estimates used in studies of workers exposed to external radiation. *Health Phys.* **74**, 22-29, 1998.

**Tables.**

| Cause of Death      | SMR non-rw | Obs non-rw | Exp non-rw | SMR rw | Obs rw | Exp rw | SMR all | Obs all | Exp all | Rate ratio |
|---------------------|------------|------------|------------|--------|--------|--------|---------|---------|---------|------------|
| Lymphatic leukaemia | 0          | 0          | 1.53       | 292    | 4      | 1.37   | 138     | 4       | 2.90    | -          |
| Myeloid leukaemia   | 0          | 0          | 2.19       | 99     | 2      | 2.03   | 47      | 2       | 4.22    | -          |
| Total leukaemia     | 0          | 0          | 7.96       | 113    | 9      | 8.00   | 56      | 9       | 15.96   | -          |

**Table 2a. Leukaemia mortality for BNFL from 1947-1968; rate ratios, adjusted for site, age, sex, calendar year, industrial status and worker status.**

**Obs;- observed deaths, Exp:- Expected number of deaths, non-rw:- non-radiation worker, rw:-radiation worker.**

| Cause of Death              | SMR non-rw | Obs non-rw | Exp non-rw | SMR rw | Obs rw | Exp rw | SMR all | Obs all | Exp all | Rate ratio |
|-----------------------------|------------|------------|------------|--------|--------|--------|---------|---------|---------|------------|
| Lymphatic leukaemia         | 106        | 11         | 10.42      | 76     | 12     | 15.84  | 88      | 23      | 26.26   | 0.68       |
| Acute lymphatic leukaemia   | 44         | 1          | 2.27       | 54     | 2      | 3.72   | 50      | 3       | 5.99    | 1.13       |
| Chronic lymphatic leukaemia | 115        | 9          | 7.81       | 86     | 10     | 11.63  | 98      | 19      | 19.44   | 0.66       |
| Myeloid leukaemia           | 74         | 15         | 20.32      | 93     | 29     | 31.04  | 86      | 44      | 51.35   | 0.94       |
| Acute myeloid leukaemia     | 64         | 9          | 13.96      | 84     | 18     | 21.43  | 76      | 27      | 35.39   | 0.84       |
| Chronic myeloid leukaemia   | 103        | 6          | 5.84       | 112    | 10     | 8.90   | 109     | 16      | 14.74   | 1.08       |
| Total leukaemia ex CLL      | 91         | 23         | 25.18      | 102    | 39     | 38.29  | 98      | 62      | 63.47   | 0.91       |
| Total leukaemia             | 94         | 32         | 34.04      | 95     | 49     | 51.50  | 95      | 81      | 85.54   | 0.84       |

**Table 2b. Leukaemia mortality for BNFL from 1968-1995; rate ratios, adjusted for site, age, sex, calendar year, industrial status and worker status.**

|      | Cause of Death         | SMR non-rw | Obs non-rw | Exp non-rw | SMR rw | Obs rw | Exp rw | SMR All | Obs all | Exp all | Rate ratio |
|------|------------------------|------------|------------|------------|--------|--------|--------|---------|---------|---------|------------|
| BNFL | Total leukaemia        | 76         | 32         | 42.00      | 97     | 58     | 59.50  | 89      | 90      | 101.50  | 1.01       |
|      | Total eukaemia ex CLL  | 69         | 23         | 33.13      | 99     | 46     | 46.29  | 87      | 69      | 79.42   | 1.06       |
| SPR  | Total leukaemia        | 120        | 11         | 9.19       | 110    | 30     | 27.15  | 113     | 41      | 36.34   | 1.05       |
|      | Total leukaemia ex CLL | 123        | 9          | 7.30       | 106    | 22     | 20.83  | 110     | 31      | 28.13   | 0.90       |
| SEL  | Total leukaemia        | 55         | 5          | 9.14       | 82     | 20     | 24.42  | 74      | 25      | 33.56   | 0.89       |
|      | Total eukaemia ex CLL  | 53         | 4          | 7.54       | 82     | 16     | 19.41  | 74      | 20      | 26.95   | 0.89       |
| CAP  | Total leukaemia        | 69         | 16         | 23.06      | 89     | 4      | 4.49   | 73      | 20      | 27.55   | 0.90       |
|      | Total eukaemia ex CLL  | 56         | 10         | 17.81      | 119    | 4      | 3.37   | 66      | 14      | 21.18   | 1.38       |
| CHX  | Total leukaemia        | 0          | 0          | 0.61       | 116    | 4      | 3.44   | 99      | 4       | 4.05    | .          |
|      | Total leukaemia ex CLL | 0          | 0          | 0.49       | 149    | 4      | 2.68   | 126     | 4       | 3.17    | .          |

**Table 3. Leukaemia mortality for BNFL and sites from 1946-1995; rate ratios, adjusted for site, age, sex, calendar year, industrial status and worker status.**

**SPR-Springfields site; SEL-Sellafield site; CAP Capenhurst site; CHX Chapelcross site.**

|                                     | Leukaemia |                               |    | Leukaemia ex CLL |                               |    |
|-------------------------------------|-----------|-------------------------------|----|------------------|-------------------------------|----|
|                                     | Trend     | ERR (90% CI)                  | no | Trend            | ERR (90% CI)                  | no |
| BNFL all workers                    | 1.84      | 0.94 (-0.55 - 3.72)           | 90 | 2.17             | 4.11 (0.74-10.9)              | 69 |
| BNFL rw                             | 2.02      | 3.32 (0.04 - 10.18)           | 58 | 2.15             | 3.64 (-0.13 – 11.22)          | 46 |
| BNFL rw adjusted dosimetry          | 2.70      | 3.87 (0.53 - 10.9)            | 58 | 2.99             | 4.46 (0.74 - 12.60)           | 46 |
| SEL all workers                     | 1.73      | 4.44 (0.51-15.2)              | 25 | 2.39             | 7.99 (1.50-29.5)              | 20 |
| SEL rw                              | 1.98      | 5.02 (0.18 - 21.95)           | 20 | 2.27             | 8.26 (0.85 – 42.66)           | 16 |
| SEL plutonium and radiation workers | 0.90      | pu+rw<br>1.38 (-0.70 – 16.66) | 11 | 0.61             | pu+rw<br>0.93 (-0.89 - 17.92) | 8  |
|                                     |           | rw<br>3.53 (<-2.93 - 24.13)   | 9  |                  | rw<br>7.49 (<-3.87- 68.79)    | 8  |
| SEL rw adjusted dosimetry           | 2.67      | 5.72 (0.73 – 24.00)           | 20 | 3.11             | 9.93 (1.63- 55.60)            | 16 |
| SPR all workers                     | -0.70     | -1.97 (<-2.21-4.23)           | 41 | -1.39            | -1.97 (<-2.14-4.20)           | 31 |
| SPR rw                              | -0.32     | -1.31 (<-2.10-10.12)          | 30 | -1.14            | -1.97 (<-2.23-6.11)           | 22 |
| SPR rw adjusted dosimetry           | -0.33     | -1.32(<-1.83– 10.30)          | 30 | -1.15            | -1.71 (<-1.96-25.00)          | 22 |

**Table 4. Trend results and excess risk estimates for BNFL and for Sellafield and Springfields from the cohort analysis. pu- plutonium workers**

| Leukaemia Type                | ICD9 Code                         | Deaths | Registrations |
|-------------------------------|-----------------------------------|--------|---------------|
| Total leukaemia               | 204.0-208.9                       | 111    | 67            |
| CLL                           | 204.1, 207.8                      | 38     | 27            |
| Total leukaemia excluding CLL | By difference                     | 73     | 40            |
| ALL                           | 204.0, 204.2                      | 4      | 5             |
| AML                           | 205.0, 205.2, 206.0, 206.2, 207.0 | 31     | 17            |
| CML                           | 205.1, 205.3, 206.1               | 22     | 12            |

**Table 5. Distribution of leukaemia, by sub-type, in the case-control study. The mortalities are those cases that had leukaemia as either the underlying or contributory cause of death.**

| Site | Male industrials | Male non-industrials | Female industrials | Female non-industrials | Total    |
|------|------------------|----------------------|--------------------|------------------------|----------|
| SPR  | 41 (21)          | 6 (5)                | 4 (2)              | 0                      | 51 (28)  |
| SEL  | 21 (15)          | 12 (3)               | 0 (1)              | 0                      | 33 (19)  |
| CAP  | 13 (10)          | 7 (4)                | 1 (1)              | 1 (1)                  | 22 (16)  |
| CHX  | 5 (3)            | 0 (1)                | 0                  | 0                      | 5 (4)    |
| BNFL | 80 (49)          | 25 (13)              | 5 (4)              | 1 (1)                  | 111 (67) |

**Table 6. Distribution of mortality (registration) cases by sex and industrial status across the sites.**

| Variable           |      | Cases Mortality | Controls Mortality | Cases Registration | Controls Registration |
|--------------------|------|-----------------|--------------------|--------------------|-----------------------|
| Age of case        | Mean | 63.6            | 63.5               | 63.2               | 63.2                  |
|                    | sd   | 14.0            | 13.9               | 13.7               | 13.6                  |
| Year of employment | Mean | 1956            | 1957               | 1957               | 1958                  |
|                    | Sd   | 6.9             | 9.8                | 7.7                | 9.6                   |
| Year of case       | Mean | 1982            | 1982               | 1983               | 1983                  |
|                    | sd   | 9.6             | 9.6                | 5.8                | 5.8                   |
| Dose (mSv)         | Mean | 51.7            | 42.4               | 51.1               | 40.7                  |
|                    | sd   | 120             | 102                | 132                | 94                    |

**Table 7. Characteristics of cases and controls**

| Variable  |           | Cases Mortality | Mean dose Mortality | Cases Registrations | Mean dose Registrations |
|-----------|-----------|-----------------|---------------------|---------------------|-------------------------|
| Age       | <30       | 4               | 1.37                | 2                   | 11.51                   |
|           | 30-40     | 2               | 52.05               | 4                   | 36.03                   |
|           | 40-50     | 11              | 20.57               | 4                   | 17.23                   |
|           | 50-60     | 25              | 37.01               | 13                  | 60.06                   |
|           | 60-70     | 31              | 47.02               | 21                  | 45.55                   |
|           | 70+       | 38              | 57.45               | 23                  | 37.96                   |
| yoe       | <1950     | 27              | 62.15               | 13                  | 61.44                   |
|           | 1950-1960 | 62              | 47.63               | 39                  | 46.19                   |
|           | 1960-1970 | 17              | 15.65               | 11                  | 13.34                   |
|           | 1970-1980 | 4               | 11.25               | 3                   | 25.88                   |
|           | >1980     | 1               | 0.79                | 1                   | 1.80                    |
| Dose (Sv) | 0         | 38              | 0                   | 29                  | 0                       |
|           | 0-10      | 36              | 3.47                | 20                  | 3.76                    |
|           | 10-20     | 4               | 15.72               | 1                   | 14.48                   |
|           | 20-50     | 11              | 31.92               | 6                   | 32.69                   |
|           | 50-100    | 5               | 76.25               | 2                   | 74.07                   |
|           | 100-200   | 7               | 132.54              | 3                   | 137.54                  |
|           | 200-300   | 1               | 242.29              | 0                   | 244.25                  |
|           | 300-400   | 6               | 356.64              | 2                   | 334.84                  |
|           | 400+      | 3               | 563.80              | 4                   | 506.58                  |

**Table 8. Mean dose, mSv, distribution of mortality and registration cases with respect to age, year of entry and dose group.**

| Site      | Cases Mortality Dose mSv (sd) | Controls Mortality Dose mSv (sd) | Cases Registrations Dose mSv (sd) | Controls Registrations Dose mSv (sd) |
|-----------|-------------------------------|----------------------------------|-----------------------------------|--------------------------------------|
| SPR       | 15.1 (31)                     | 22.7 (36)                        | 8.8 (19.2)                        | 21.5 (35.9)                          |
| SEL       | 138.2 (184)                   | 92.9 (162)                       | 101.8 (190)                       | 86.1 (145)                           |
| SEL pu+rw | 210.86 (162)                  | -                                | 327.3 (112)                       | -                                    |
| SEL rw    | 92.42 (182)                   | -                                | 54.4 (169)                        | -                                    |
| CAP       | 0.49 (2.0)                    | 1.26 (4.7)                       | 0.69 (2.31)                       | 1-41 (5.6)                           |
| CHX       | 78.0 (146)                    | 90.4 (122)                       | 251.8 (184)                       | 84.7 (106.2)                         |
| BNFL      | 51.7 (120)                    | 42.4 (102)                       | 51.1 (132)                        | 40.7 (94)                            |

**Table 9. Distribution of doses for cases and controls at the different sites.**

|      | Total leukaemia All workers (90%CI)    | Total leukaemia Radiation Workers (90%CI) | Total leukaemia ex CLL All workers (90%CI) | Total leukaemia ex CLL Radiation Workers (90%CI) |
|------|--|---|--|--|
| BNFL | 1.20<br>(<-2.81 - 4.95)<br>(111 cases) | 0.89<br>(<-2.81 - 4.73)<br>(71 cases)     | 2.46<br>(<-2.56 - 7.87)<br>(73 cases)      | 2.00<br>(<-2.68 - 7.66)<br>(45 cases)            |
| SPR  | -4.41<br>(<-9.32 - 1.31)<br>(51 cases) | -3.50<br>(<-3.48 - 4.51)<br>(37 cases)    | -5.60<br>( <-5.61 to -1.790)<br>(33 cases) | -5.40<br>(<-6.40 - 1.96)<br>(22 cases)           |
| SEL  | 3.51<br>(<-5.29 - 13.15)<br>(33 cases) | 2.30<br>(<-4.46 - 11.11)<br>(28 cases)    | 9.96<br>(<-8.78- 40.83)<br>(21 cases)      | 4.87<br><-4.99 - 22.03)<br>(19 cases)            |

**Table 10. Excess relative risk estimates, Sv<sup>-1</sup>, of mortality for all workers and radiation workers; by site.**

|      | Total leukaemia<br>All workers         | Total leukaemia<br>Radiation Workers     | Total leukaemia ex<br>CLL All workers   | Total leukaemia ex<br>CLL<br>Radiation Workers |
|------|--|--|---|--|
| BNFL | 1.45<br>(<-2.31 – 6.37)<br>(67 cases)  | 7.47<br>(<-3.81- 26.14)<br>(35 cases)    | 3.33<br>(<-2.81 to 13.25)<br>(40 cases) | 9.29<br>(<-4.68- 39.53)<br>(23 cases)          |
| SPR  | -4.14<br>(<-4.29 – 0.11)<br>(28 cases) | -4.81<br>(<-10.15 – 18.57)<br>(16 cases) | -6.35<br>(<-6.42- 1.82)<br>(17 cases)   | -3.19<br>(<-11.65- 24.26)<br>(11 cases)        |
| SEL  | 2.20<br>(<-3.27 – 11.53)<br>(19 cases) | 10.62<br>(<-5.85 - 70.81)<br>(13 cases)  | 8.88<br>(<-8.16-61.20)<br>(12 cases)    | --   |

**Table 11. Excess relative risk estimates, Sv<sup>-1</sup>, of morbidity for all workers and radiation workers; by site.**